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Assessing Uncertainties in the Probability of Raid Annihilation

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ABSTRACT: *The Probability of Raid Annihilation, P_{RA}, is the measure of a single ship with its combat systems to detect, control, engage and defeat a specified raid of threats within a specified level of probability in an operational environment. The Navy, led by Program Executive Office for Theater Surface Combatants (PEO TSC), is developing an assessment process for P_{RA} that uses an innovative combination of live testing and a simulation, the P_{RA} Federation. A crucial element in the assessment process is identifying the uncertainties in the P_{RA} measure, in particular those associated with the natural environment.*

The P_{RA} Federation is unusual in that a given threat reacts to the combined ship defenses while all ship defenses simultaneously see the common threat. This complexity of interactions with the associated environmental effects makes it very difficult to determine uncertainties in the P_{RA} due to environmental considerations. To further complicate matters, the P_{RA} Federation is designed to permit the interchange between operational and test scenarios, thereby supplementing live testing with simulation results. This interchange capability demands that the relation between the real world and implemented environment be captured in detail so that resulting uncertainties in the P_{RA} due to the environment can be well-understood and documented.

Using the P_{RA} measure as a specific example, this paper illustrates a new technique in evaluating how the outcome of simulations is affected by uncertainties in the natural environment provided. The Environment Concept Model (ECM) process, developed under the Navy MARitime Environmental Data Standards (MARVEDS) program for use in developing environmental requirements, is applied to identify and document the complexities within the P_{RA} Federation and the links with the operational and test environments. In particular, the assumptions and constraints in modeling the environmental effects are captured in detail to assess the appropriate level of fidelity and consistency required in the environmental representation. In other words, the ECM process links the simulation outcome, the P_{RA} measure, back to the required natural environment representation. Using the same procedure, the uncertainty in the P_{RA} measure can be linked mathematically back to the uncertainty in the required natural environment representation and vice versa. Thus, the ECM process and documentation capture the traceability needed not only to determine natural environment representation requirements but also to evaluate how uncertainty in that environmental representation affects the uncertainty simulation outcome.

1. Introduction

This paper describes a promising methodology to assess uncertainties in the Probability of Raid Annihilation (P_{RA}) Measure of Effectiveness (MOE) used by the Navy as part of the assessment for ship self defense. The methodology builds on a number of tools, techniques and programs in Modeling & Simulation (M&S). These, including MARVEDS, are described very briefly in Section 2, Background, together with references for additional information. The P_{RA} process and the role that the ECM plays are described in Section 3. The new aspect of ECM, in addition to capturing environmental

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requirements and as a basis for validation, is provided in Section 4 with Conclusions following in Section 5.

2. Background

The Navy Modeling & Simulation Office (N6M) has established the MARitime Environmental Data Standards (MARVEDS) program to develop and promote standards for representing and using the integrated natural environment in simulations. Standards can include aspects of data representations such as parameters, spatial and temporal resolutions, formats and coordinate systems. Standards can also address serving methods for delivering dynamic data and even best practices for applying such data in effects models. The development of such standards is based, in part, on the requirements for the integrated natural environment in Naval M&S. However, existing requirements do not provide the level of detail necessary to develop such standards. Therefore, MARVEDS is developing a formalism, including a living document, to capture, collate, and coalesce the integrated natural environment requirements for the Navy programs and offices involved in developing simulations. This formalism includes the Environment Concept Model (ECM), a procedure and a process, to unambiguously describe the integrated natural environment information needed by a simulation and the how that information is used in the simulation itself. The role that MARVEDS plays in M&S is graphically presented in Figure 1, which is a variation of the Environmental Reference Model. For further information, contact Dr. S. K. Numrich, the MARVEDS Program Manager, at Numrich@ait.nrl.navy.mil.

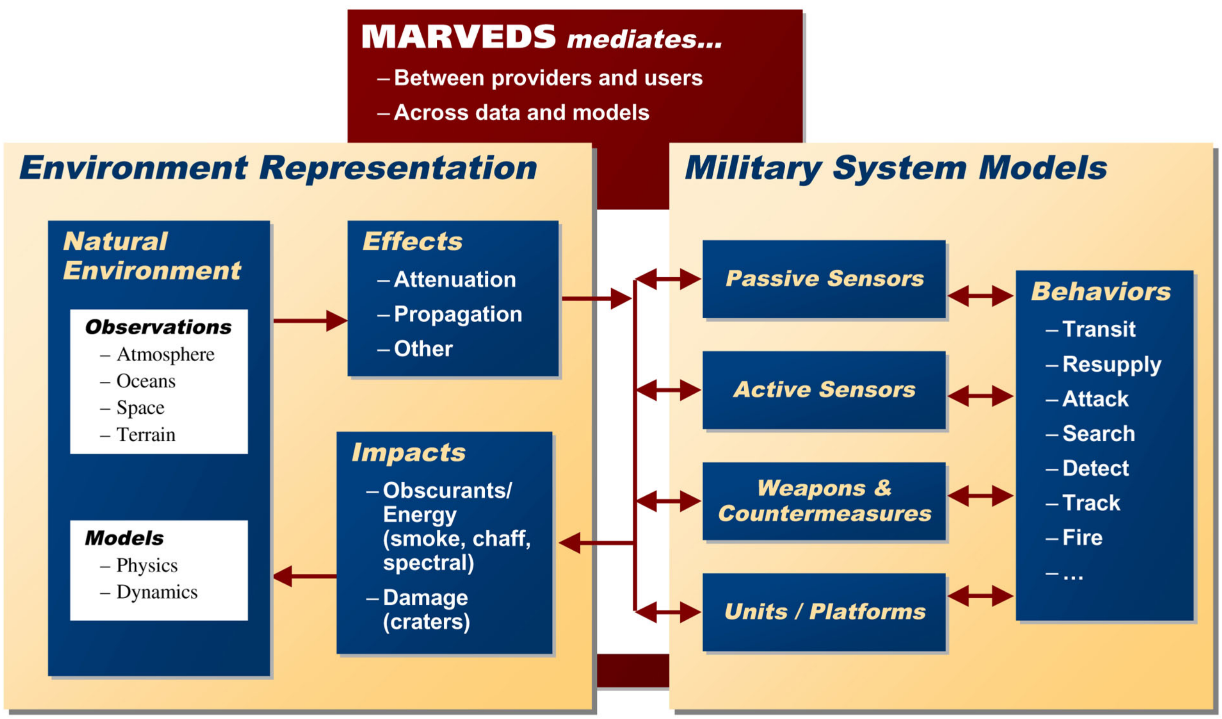

Figure 1. The Role of MARVEDS in Simulation Development

The formalism being developed by MARVEDS is based on conceptual modeling, a common technique for representing information systems, especially ones involving complex or ill-defined problems. In conceptual modeling the system is viewed as objects that can interact in various ways. Each object has associated properties, not immutable, that determine its interactions with other objects. The process of developing a conceptual model then involves determining how a system can be expressed in terms of objects, properties and interactions. The concept model provides a common basis by which stakeholders and developers can agree on the purpose and goals of the system. In particular, conflicts and inconsistencies can be identified and resolved. The concept model should capture the agreements and decisions that then lead to the requirements for the system. The requirements, in turn, form the basis of the validation process for the system. (See Reference 1 for more information on conceptual modeling.)

Conceptual modeling has many applications and plays an integral role in the FEDEP process. DMSO has invested

in the Concept Model of the Mission Space (CMMS), now the Functional Description of the Mission Space (FDMS). The documentation for the FEDEP and the CMMS do not address the level of detail needed to capture the integrated natural environment requirements as needed to handle sensor effects in Navy M&S. These and other DMSO programs are found on the DMSO Web Site: http://www.dmso.mil

The MARVEDS Program and the Integrated Ship Defense (ISD) M&S Pilot Program collaborated to achieve a consistent natural environment representation across federates that use legacy codes. (See Reference 4.) The representation is said to be internally consistent if it has been developed in accordance with known physical and dynamical constraints. Internal consistency is commonly imposed on the pre-runtime integrated natural environment representation provided as input for a simulation exercise. Achieving and maintaining a consistent integrated natural environment during runtime for a simulation or federation is much more complex. Legacy codes frequently have embedded environmental data. One code may use a constant wind of five m/s from the north while another uses a wind of one m/s blowing from the east. Further, the pre-runtime environment data may supply a wind that varies temporally in magnitude and direction. Thus, the winds in the legacy codes and in the pre-runtime data are inconsistent with each other.

Conflicts in the legacy codes have to be resolved to achieve consistency in the environment but first such conflicts have to be identified and documented. (See Reference 4 for examples.) Concept modeling is ideal for this purpose and, further, is already in use by the M&S community.

The ECM is a process-based product in the form of an electronic document. The resulting document is composed of three major sections. First, the document describes the real world scenario(s) the simulation will represent. The military systems and personnel are identified, as well as the actions they perform. Often, the scenarios are broken down into smaller vignettes, to clarify the representations. The document's second section describes the land/sea/air modeling needed to satisfy all the needed terrain, weather and ocean phenomena. The ECM documents the independent and dependant variables, algorithms and logic. The document's third section revisits the second section's need-based description, from a different perspective. The third section describes the land/sea/air modeling as actually implemented, with limitations imposed by science understanding as well as project schedule and budget considerations. (See Reference 3 for more information on the ECM.)

We use the Unified Modeling Language as the analysis and design language to describe environment representations in the ECM. Reference 5 provides an introduction to this standards-based analysis and design language, and Reference 2 provides a detailed user guide.

The extensive ECM documentation also includes details of simulation objects, models, assumptions, constraints, agreements and other related reference material. As such, this documentation can provide the basis for validation of the system. (See Reference 6.)

3. Probability of Raid Annihilation (P_{RA})

3.1 Definition

The Probability of Raid Annihilation is defined as the ability of a particular stand-alone ship, as an integrated system, to detect, control, engage and defeat a specified raid of anti-ship missile (ASM) threats with a specified level of probability in the operational environment. The P_{RA} MOE is a system of systems measure that is levied on the ship defense suite as a whole to properly detect, control, and engage (annihilate) a raid of incoming threat ASMs. The ability to directly test the capability of a ship to withstand a raid is not practical. Therefore, a combination of live tests and simulations will be used. In fact, the P_{RA} Federation is unique in that simulation will be able to incorporate directly the results from the live testing.

In addition to the P_{RA} metric, an evaluation is needed of the causes of uncertainties in the system, including an estimate of the uncertainty in the P_{RA} metric itself. Models and simulations are by definition subsets of reality because of the constraints, and assumptions imposed. These assumptions and constraints introduce uncertainties. However, live testing is also subject to uncertainties introduced by limited scenarios and observational errors. This paper describes a process by which these uncertainties can be documented, analyzed and evaluated to ascertain their impact on the final outcome of the determination of the Probability of Raid Annihilation.

The Navy, led by PEO TSC, has convened a task group to evaluate the P_{RA} process and, specifically, the environmental effects that must be considered. This task group includes subject matter experts in the areas of ship defense, threats, radars, electronic warfare and the natural environment. This task group has collaborated to define the model of the P_{RA} displayed here. Starting with a simple framework, as shown in Figure 2, additions have been made so that an increasingly detailed system has been captured in the context of this simple model.

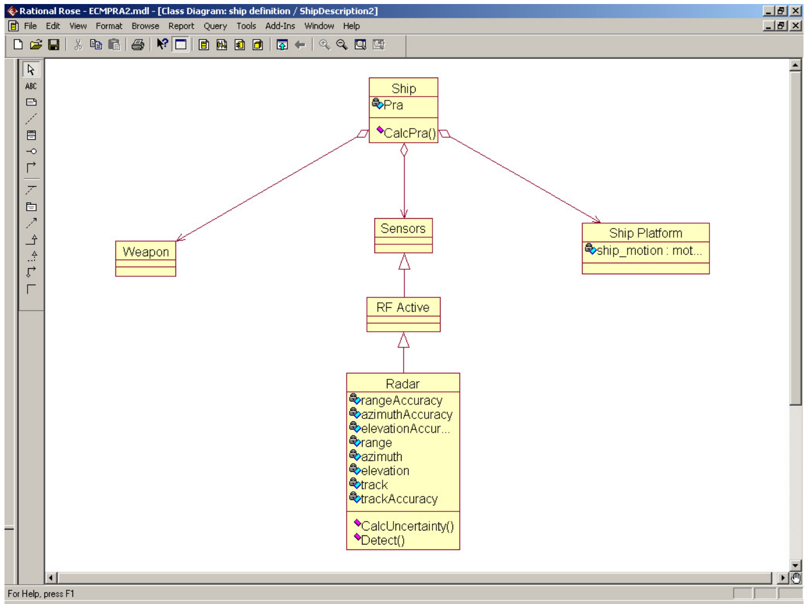

Figure 2

3.2 Current application

Figure 3 shows more detail in the P_{RA} simulation. Again, however, the detail is shown only for one subsystem, the radar. The overall system consists of the RAM missile and associated launch and guidance systems, decoy systems, and electronic warfare systems. A complete evaluation of system performance, system uncertainties, and the effects of the environment require detailed information on all of these subsystems.

The primary goal of this work is to document the assumptions in the development of the simulation from a description of the real world. The first step of this is to compile a list of the various effects that can act on the system. Next, it is necessary to either incorporate the effect or explain and document why it couldn't or shouldn't be included. Table 1 contains such a list of environmental effects that could impact a radar or RF seeker. (This information is displayed in table form, rather than in the Rational Rose Representation used in other Figures, to save space.)

Only the sea clutter and propagation effects are retained for evaluation, primarily because appropriate computer models of the other effects are not readily available. However, the other effects are included in the overall concept model with explanations regarding why they have not been included, facilitating later upgrades and reuse.

	Radar/RF Seeker
Environmental Effects on system	Sea/Land Clutter Discrete clutter Rain/volume clutter Bird/insect clutter Propagation Noise Electromagnetic Interference Wind loading bends array

Table 1

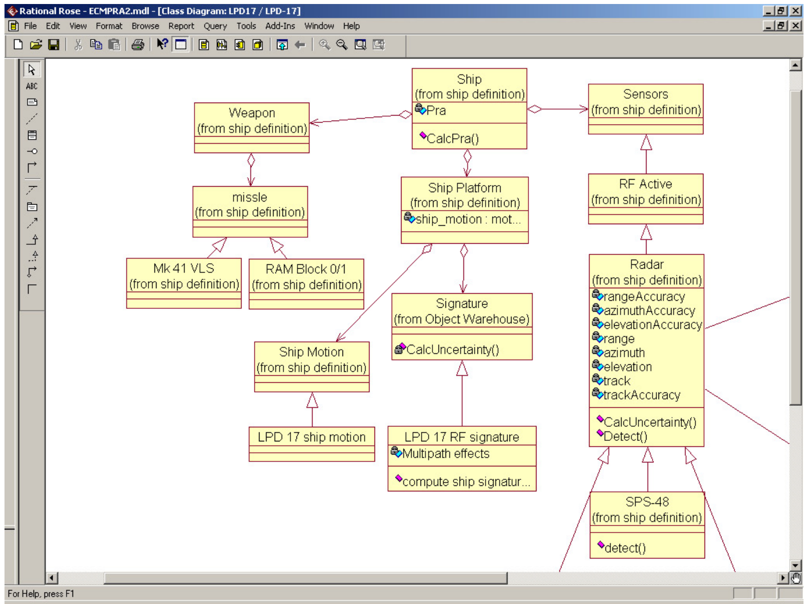

Figure 3

The environmentally relevant parameters for the radar are shown in Figure 4. The arrows with the small heads define sources of information for an object. For example the “Radar” object will request range information from the “RFPropagation” object and sea clutter from the “SeaClutter” object. In turn the “SeaClutter” object will request sea state information from the “SeaState” object.

For the purposes of this paper the uncertainties will be traced from the determination of temperature profile and hence radar propagation performance to the impact on the final determination of P_{RA} for this ship. It is understood that this process must be followed for each subsystem in the simulation to develop a complete view of their contribution to the overall uncertainty calculation.

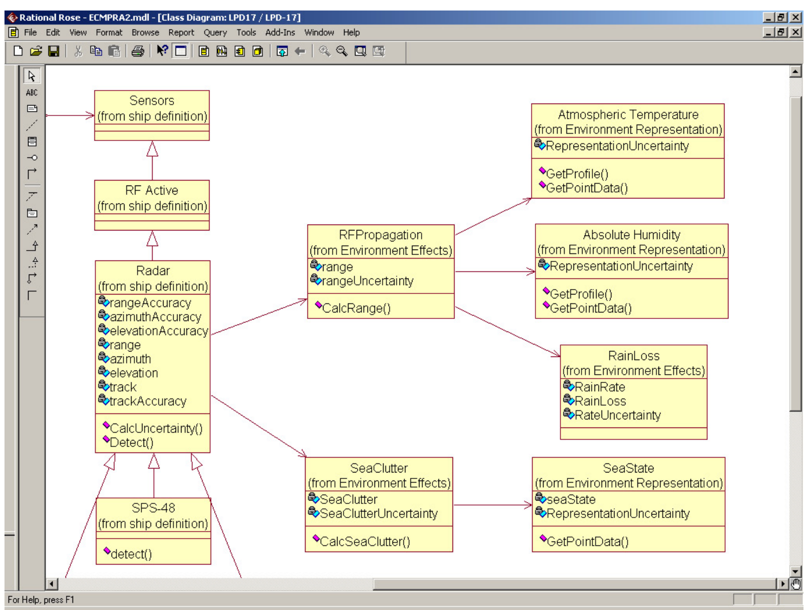

Figure 4

4. ECM Captures Uncertainty Information

4.1 Definition of Uncertainty

According to the National Institute of Standards and Technology (NIST), uncertainty can be described as:

> "The uncertainty (of measurement) parameter associated with the result of a measurement characterizes the dispersion of the values that could reasonably be attributed to the measurand. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
>
> Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.
>
> It is understood that the result of the measurement is the best estimate of the value of the measurand, and that *all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion."* (Italics are the authors'.)

(Reference:
http://physics.nist.gov/cuu/Uncertainty/glossary.html,
June 27, 2001)

4.2 P_{RA} Scenario Definition

The P_{RA} scenario consists of a single ship steaming independently when attacked by a saturation raid of anti-ship missiles. This is the situation described in UML in Figure 2.

The ability of a ship to defend itself depends upon its ability to detect a threat, track a threat, and ultimately destroy the capability of the threat to damage the ship. The detection of a threat consists of two elements; one is the detection of the presence of a potential threat and next is to determine if the contact is hostile and if so is it a threat to the ship. Once a contact is detected the track of that contact must be maintained until positive determination as a threat is made and then the fire control system must be able to compute the fire control solution and launch a defensive weapon. This may be for a hard kill, and electronic attack or a combination of the two. Finally there must be an assessment as to whether or not the threat was killed. This process must be repeated for each of the threats in the raid. (See Reference 7 for more information about threat representation in simulations of ship self defense.)

4.3 Environmental Uncertainties

4.3.1 Measurement

Any simulation provides many opportunities for uncertainty but the focus here is on those related to the natural environment, for both measurements and models. The first major source is in the measurement of the environmental parameters, e.g., temperature, winds and currents. Instrumentation has inherent errors as does the ability to record and report these measurements. Measurements are made at "points" over a period of time. The size of this "point" and the length of time over which the measurement is made are sources of uncertainties in the value of a parameter to be recorded. While there are standard methods for obtaining and analyzing most measurements, information regarding the errors or uncertainties is usually not available. Often, only isolated values of a parameter are recorded and reported for a specific place and time.

4.3.2 Representation

Measurements of the ocean and atmosphere environment have less obvious limitations as well. The observational network is very limited, both spatially and temporally. Measurements are recorded for a specific location (including altitude) and time, but are often used for a much larger area and over considerable time periods. Are such point measurements truly representative? When a measurement is made at an airport, is it valid for a location near a river five miles away? The answer to that question is context dependent. For data represented on a grid, seldom are the measurements taken at the actual grid point. The evaluation of the importance of these difficulties can only be known when placed in the context of the effect on the system of interest. This evaluation must address the relative magnitude of the impact of the uncertainties of the system components.

To counter the limitations imposed by a limited observation network, environmental scientists commonly use a judicious combination of observations and numerical models, encompassing physical and dynamical constraints, to produce natural environment representations. Again, the use of numerical models imposes uncertainties on the resulting natural environment representation.

4.3.3 Environment Effects

For this discussion of uncertainty, two environmental effects are of primary interest: the clutter created by the surface of the ocean and the anomalous propagation created by ducting conditions. Uncertainty in these parameters is introduced during at least three events: the observation and the extrapolation to the location and time of interest of the relevant environmental parameters, and the model of the effect of these phenomena. This information is also captured in the Environment Concept Model.

It is important in the discussion and calculation relating to uncertainty to determine if the items of interest are independent or correlated. This information can be documented in the Environment Concept Model as described below. The method in which the uncertainty behavior of an object is implemented will make use of this information. In our example it is necessary to capture when the sea state is correlated with the anomalous radar propagation and when it is not.

4.3.4 Documented in the Environment Concept Model

In addition to defining environmental requirements and providing a basis for validation of the simulation, the Environment Concept Model provides the mechanism to capture and document the uncertainty and the relationship of uncertainty with other elements of the system. Within each object there exists attributes and behaviors. The characteristics of uncertainty may be unique to each object or entity. Therefore it is beneficial to allow each object to calculate its own uncertainty. This behavior stores the measure of uncertainty as one of the objects attributes. At this stage of the work the uncertainty calculations are described in text and are calculated off line. The ability to instantiate behaviors as computer code is a capability of the Rational Rose implementation of UML that is yet to be exploited.

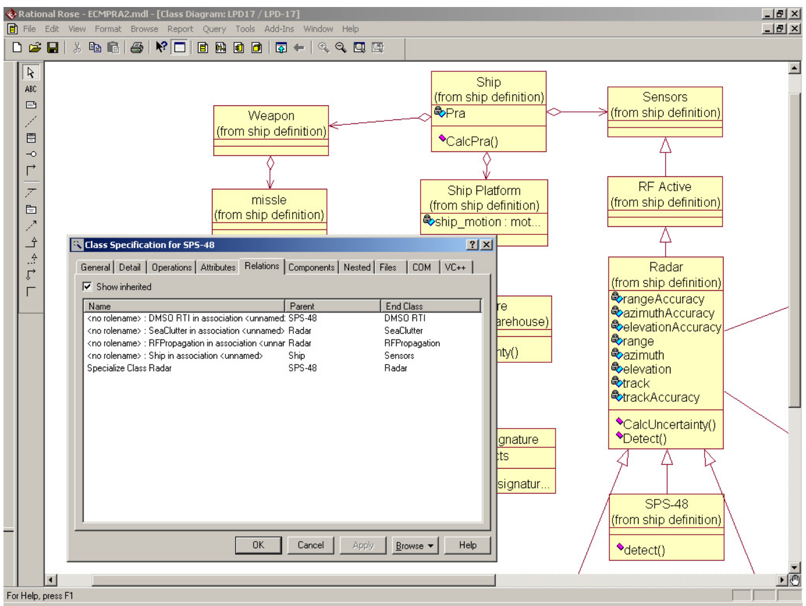

Figure 5

4.4 P_{RA} Uncertainty Calculations

The probability of raid annihilation depends upon the ability of the ship's systems to detect, control and engage the threat. The ability of these systems to perform is dependent upon the nature of the raid. The subsystems and components that represent the ship's capabilities are depicted as objects in the Figures above. One of the attributes of each component captured by the Environment Concept Model is the uncertainty of the performance of that component. The relationship of each component is also depicted graphically. The ability to ensure that each relationship is considered is facilitated by the object description as shown in Figure 5.

In the inset it is seen that the SPS-48 must consider the sea clutter and radar propagation because it is a special case of radar. If one then looks at the sea clutter object, in the inset in Figure 6, it is seen that the sea state object provides information for clutter calculations.

It is also seen that sea clutter is used by a number of other objects and therefore these must be considered when manipulating the SeaClutter object. This documentation is

used determine the degree of independence of each of the objects and its behaviors when evaluating uncertainty.

As was stated earlier, the current process of evaluation depends upon manually following the relationships and calculations contained in the object model.

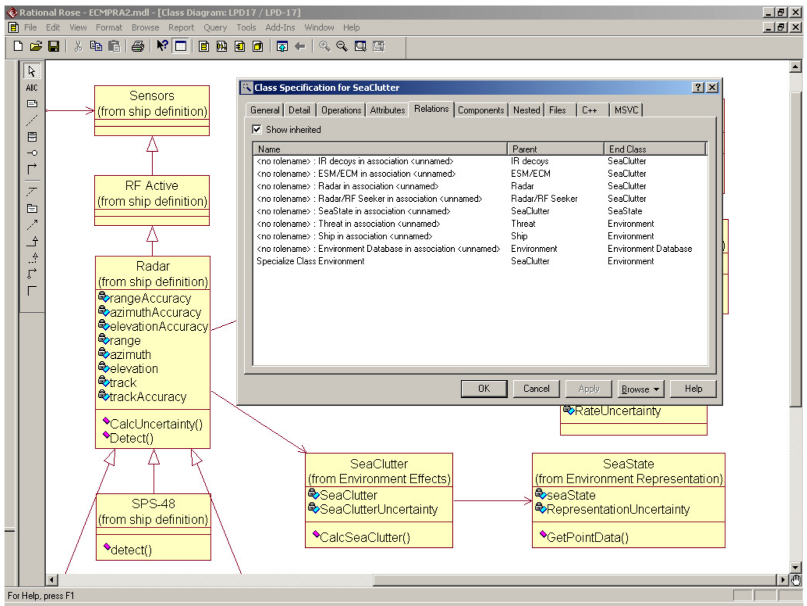

Figure 6

4.5 Relationship of Environment and Other Uncertainties

4.5.1 Scenario

The definition of a representative environment for a particular scenario remains an issue. The environmental conditions used in the simulation may be as big a factor in the system performance as any of the other subsystems. In the scenario of interest, if the potential raid and subsequent engagement occurs in an area of intense rain and wind, the remainder of the subsystems will most likely be of little consequence. On the other hand, if the raid occurs in a clear, calm day with a moderate sea state and no ducting, then the environment is of little consequence. The uncertainty calculations are related to the calculations needed to evaluate the relative importance of the various subsystems. Low uncertainty in a subsystem of minor importance in a specific scenario is of little interest. And of course, high uncertainty in a subsystem of major importance is a source of concern in the validity of a simulation. One value of a well-defined concept model is to partition the subsystems into these categories.

4.5.2 System

The Rose UML description of the system allows the simulation designer to document the characteristics of the system. This process allows the designer to capture information from subject matter experts and other documentation. When properly employed the relationship among the subsystems and components is documented and maintained in a readily available format in the object representations as seen in the above illustrations. In the context of this work, one of the subsystems is the natural environment.

4.5.3 Example

In the subset of the P_{RA} system provided above the system is tracked through the ECM from the high level view down to the natural environment parameters. Figures 3-7 show that there are multiple paths from the ship behavior down to one of the natural environment parameters, say, the atmospheric temperature. One such path, illustrated in Figure 7, can be demonstrated as follows:

1. P_{RA} MOE is a nonlinear function of the probabilities of kill, $P(K_{ij})$, for each threat, i, and each ship weapon, j.
2. $P(K_{ij})$ is a nonlinear function of probabilities of detection, $P(D_i)$, control, $P(C_i)$, and engagement $P(E_{ij})$.
3. $P(D_i)$ is a nonlinear function of the probability, Φ_I(sensor k), that each individual ship sensor, such as the RF (radio frequency) radar, can detect a given threat.

4. Φ_I(RF radar) is a nonlinear function of several factors, including RF propagation, RP, and sea clutter, SC.
5. RP is a nonlinear function of number of environmental effects, including propagation loss, PL.
6. PL is a nonlinear function of the natural environment parameters, including atmospheric temperature, T, and absolute humidity, H.

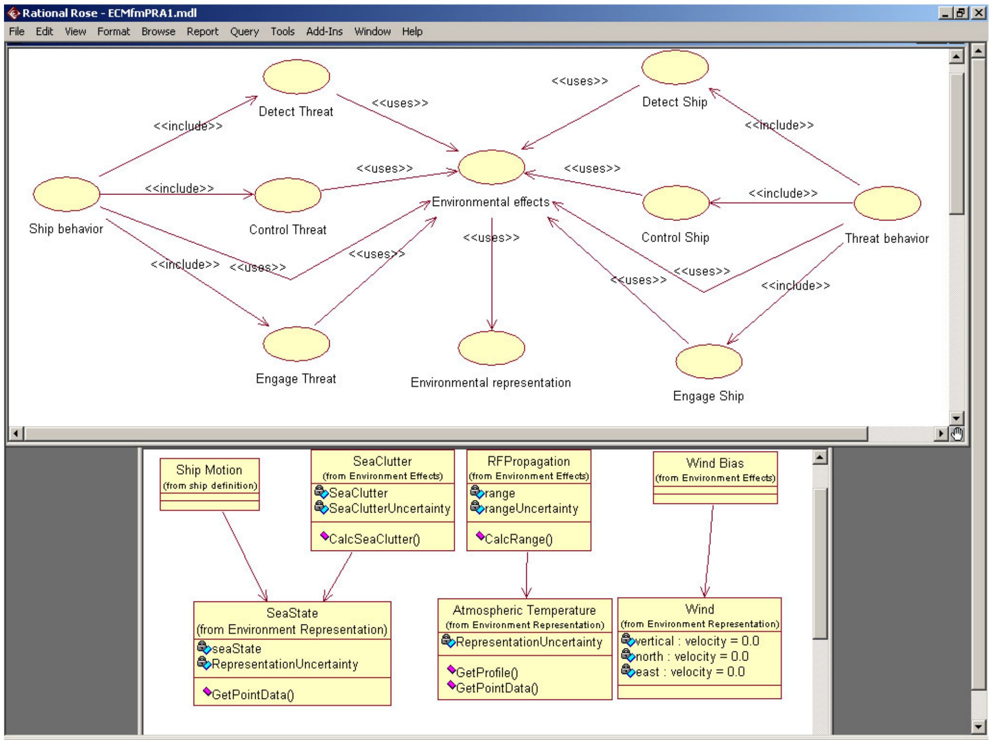

Figure 7

Only one path has been followed in steps 1-6. For example, there are several detection sensors, and sometimes duplicates of a given sensor, so several different paths could be followed in step 4. In fact, steps 2 – 5 can all involve multiple paths. Step 6, however, leads to the natural environment parameters, which are limited in number: temperature, pressure, horizontal wind speed and direction, vertical wind speed, humidity, and density as well as aerosol type and distribution. For some scenarios, chemical and biological agents are included. These natural environment parameters are not independent of each other but are related through a set of well-known physical and dynamical relations. As described in sections 4.4.1 and 4.4.2, there are uncertainties in both the measurements and representations of these parameters. How can these uncertainties be related to uncertainty in the P_{RA} MOE?

The uncertainty in the atmospheric temperature, whether measured or modeled, is a complex and largely unknown function of position and time. In addition, the uncertainty in temperature is related to the uncertainties in the other environmental parameters. Although the detailed uncertainty functions are unknown, reasonable bounds on the uncertainties are available. Then instead of T in step 6, $T \pm \Delta T$ can be inserted to calculate the propagation loss, $PL \pm \Delta PL$. The uncertainty in propagation loss is passed to the RF propagation, RP, in step 5 to determine $RP \pm \Delta RP$. In step 4, RF propagation uncertainty is passed to the probability of detection for the given radar to determine $\Phi_I \pm \Delta\Phi_I$. In step 3, the uncertainty in probability of detection by a given radar is passed to the total probability of detection relation to determine $P(D_i) \pm \Delta P(D_i)$. And so on, until in step 1, P_{RA} MOE $\pm\ \Delta P_{RA}$ MOE, is calculated.

The example described here tracks only one part of the uncertainty in the P_{RA} MOE due to uncertainty in atmospheric temperature. The atmospheric temperature appears in many of the sensor effects algorithms as well

as in other military systems models for the P_{RA} Federation. To determine how the uncertainty in atmospheric temperature totally affects the uncertainty in the P_{RA} MOE, every one of these links must be traced back and the relevant calculations performed. Then it will be possible to state that uncertainty in atmospheric temperature of a given size contributes to an uncertainty of a given size in the P_{RA} MOE.

Another level of complexity is added when additional contributing factors at any stage of the uncertainty propagation are considered. When multiple factors affect any object, the proper method of combining uncertainties must be considered. Consider, for example, the effects of multiple environmental factors on propagation loss. We define propagation loss (PL) as a function of these environmental factors (EV_i) as $PL = f(EV_1, EV_2, ...EV_n)$. If we have expressed the uncertainty of each environmental factor as a standard uncertainty $u(EV_i)$, we can calculate the standard uncertainty of the propagation loss, $u(PL)$, as

$$u^2(PL) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial EV_i}\right) u^2(EV_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \frac{\partial f}{\partial EV_i}\frac{\partial f}{\partial EV_j} u(EV_i, EV_j)$$

where $u(EV_i,EV_j)$ is the covariance associated with EV_i and EV_j. If the uncertainties of the environmental factors were expressed differently, a different method for combining them would be required.

5. Conclusion

This paper has described the use of the Environment Concept Model as a tool and technique to identify, trace and document the objects and assumptions associated with the evaluation of the Probability of Raid Annihilation. The Environment Concept Model provides the ability to define the properties of systems, models and simulations such that the relationships among these entities are also captured. Furthermore, the ECM can capture and document the specific algorithms used. As described here, the P_{RA} ECM has focused the natural environment subsystem. Finally, it has been demonstrated that the information in the ECM can be analyzed and applied to addressing the uncertainties in the P_{RA} MOE. In conclusion, the ECM can provide a tool for the tracking and evaluation of uncertainties in addition to defining requirements and providing a basis for validation and verification, as has been shown in earlier paper.

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